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MULTICRITERIA EVALUATION AND FUZZY SET THEORY: APPLICATIONS IN PLANNING FOR SUSTAINABILITY

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ABSTRACT

One of the main differences of evaluation models is between monetary and non-monetary evaluation. Cost-benefit analysis and cost-effectiveness analysis are well-known examples of a monetary evaluation. In the past decades, the degraded state of the natural environment has become a key issue, and it is increasingly taken for granted that environmental and resource problems generally have at least far reaching economic and ecological consequences. Economic-environmental evaluation and decision problems are conflictual in nature and, therefore, multicriteria techniques seem to be an appropriate modelling tool. This paper attempts to analyze in a critical way some essential aspects of social cost-benefit analysis and multicriteria decision methods. In particular, the paper deals with uncertainty and measurement problems in environmental policy analysis, seen from the viewpoint of the measurement level of information (including fuzzy set methods). Particular emphasis will be placed on methods for concerted planning evaluation.

Keywords: sustainability, evaluation, cost-benefit analysis, multicriteria methods, fuzzy sets

1. Evaluation as a Part of Planning

The planning process has become nowadays a rather complicated matter in technical, physical, social and economic respect. In order to guide a decision-maker in choosing the most appropriate choice alternative, a set of rules is required to transform the facets of a certain planning proposal into statements about society well-being. This set of rules is called an *evaluation method*.

Evaluation aims at rationalizing planning and decision problems by systematically structuring all relevant aspects of policy choices (for instance, the assessment of impacts of alternative choice possibilities). Evaluation is usually not a one-shot activity, but takes place in all phases of decision-making (for instance, on the basis of learning principles). Besides, it has to be realized that the planning environment is usually highly dynamic, so that judgements regarding the political relevance of items, alternatives or impacts may exhibit sudden changes, hence requiring a policy analysis to be flexible and adaptive in nature. Rigid evaluation techniques run the risk that an evaluation does not cover all issues of a regional, urban or environmental planning problem in a satisfactory way [29, 31].

Evaluation may be considered as a continuous activity which permanently takes place during the planning process. Even a limitation to a specific or restricted kind of evaluation does not change this characteristic, since there are always many choice-possibilities during a planning process which have to be assessed and judged. However, for reasons of clarity we will restrict in this paper the meaning of the notion "evaluation process" to the act of judging a coherent set of distinct and policy-relevant alternatives. A simultaneous consideration of all relevant aspects is important here in order to ensure that an evaluation process treats a planning issue (e.g., the evaluation of traffic circulation plans, of alternative highway routes, or of implementation schemes for physical planning) on the basis of multiple viewpoints. It is noteworthy that evaluation processes have often a cyclic nature. By "cyclic nature" is meant the possible adaptation of elements of the evaluation due to continuous consultations between the various parties involved in the planning process at hand. Such a learning process is a necessary condition to bridge the gap between technicians, researchers and planners. The degree of complexity of an evaluation process depends among others on the evaluation problem to be treated, the time and knowledge available and the organizational context [39].

According to Tinbergen, it may be useful to make a distinction between

the analytical aspect and the political aspect of public decision making.

The analytical aspect is concerned with links between all variables relevant in the decision-making process as well as with all side-conditions resulting from the economic, social and technological structure of society. This analytical aspect of a decision problem can in theory be represented by a set of formal statements or an impact model (or structural model).

The political aspect concentrates on the way in which the instruments should be manipulated to realize the policy objectives. These policy objectives can be operationalized as fixed targets to be strived for or as arguments of a community welfare function to be optimized. In particular the latter approach has received much attention in the literature about policy-making and in welfare economics.

Plan and project evaluation has become an important component of modern public planning and administration. It should be noted that different kinds of evaluation can be distinguished in a policy analysis, one of the important discriminating characteristics being between monetary and non-monetary evaluation. A *monetary evaluation* is characterized by an attempt to measure all effects in monetary units, whereas a non-monetary evaluation utilizes a wide variety of measurement units to assess the effects. Cost-benefit analysis and cost-effectiveness analysis are well-known examples of a monetary evaluation [31, 32].

The history of plan and project evaluation before World War II showed first a strong tendency towards a financial trade-off analysis. Later on much attention was focussed on cost-effectiveness principles. After World War II, cost-benefit analysis gained increasing popularity in public policy evaluation, by using willingness to pay notions, consumer surplus principles and shadow prices. Social cost-benefit analysis can be regarded as an effective kind of applied welfare economics. It consists of the following main steps [7, 14, 27, 34]:

- identification of costs and benefits
- quantification and evaluation of costs and benefits in terms of a common monetary unit
- choice of a social rate of discount
- choice of a time horizon
- construction of a one-dimensional indicator bringing together all the benefits and costs (many authors suggest the use of the net present value).

The social returns are composed of all gains and losses of all members of society whose well-being will be affected by the plan if implemented. These gains and losses are measured by the preferences of the individuals who are affected. The hypotheses underlying monetary evaluation methodologies took for granted rational choice behaviour based on a one-dimensional well defined performance indicator. The use of such conventional optimization models has been criticized from many sides. The optimizing approach is based on the assumption that different objectives can be expressed in a common denominator by means of trade-offs, so that the loss in one objective can be evaluated against the gain in another. This idea of *compensatory changes* underlies both the classical economic utility theory and the traditional cost-benefit analysis. The determination of a common denominator is, however, fraught with difficulties. Interview methods frequently provide unsatisfactory results, while revealed preference methods are only effective as an ex post procedure. From a theoretical point of view, the optimizing principle is very elegant, since it provides an unambiguous tool to evaluate alternative strategies on the basis of their contribution to community welfare. From an operational point of view, the value of the traditional optimizing approach is however, rather limited, because the specification of a community welfare function requires complete information about all possible combinations of actions, about the relative trade-offs between all actions and about all constraints prevailing in the decision-making process. Furthermore, in the past decades, the degraded state of the natural environment has become another key issue in evaluation because of the externalities involved and it is increasingly taken for granted that environmental and resource problems generally have at least far reaching economic and ecological aspects, which cannot always be encapsulated by a market system. The estimation of a project lifetime, for instance, as well as of the social rate of discount is generally overloaded with uncertainties, so that a cost-benefit analysis has to be accompanied at least by a sensitivity analysis. The limits inherent in conventional evaluation methodologies and the necessity of analyzing conflicts between policy objectives have led to a need for more appropriate analytical tools for strategic evaluation.

In the next sections we will give a more detailed discussion of some limitations of cost-benefit analysis.

2. Market Failures of Neoclassical Economics

The basic problem inherent in the use of cost-benefit analysis is the fact that the evaluation of a project must relate to an unambiguous monetary unidimensional criterion, because a comprehensive cost-benefit approach requires a transformation of all project effects into one simple monetary dimension. In classical welfare economics, prices resulting from a competitive equilibrium can be considered to be a measure of social opportunity costs. Deviations from the neoclassical model originate from the so-called "*market failures*". Market distortions such as monopoly, taxes, price regulations and disequilibria often play an important role in the economy. As a result, prices may be bad indicators of the real scarcities and pertaining social evaluations in the economy. In order to relax this limitation inherent in cost-benefit analysis, consumer surplus principles, shadow prices and willingness to pay notions were introduced [7, 14, 27, 32, 34]. The *consumer surplus* is a frequently used concept in a cost-benefit analysis in order to judge whether the project in question provides a net contribution to raising the level of aggregate consumption. A necessary condition for an effective calculation of the aggregate consumer surplus is knowledge of the demand curves for the elements of the project at hand. Unfortunately, frequently little information is available about these demand curves. The social gains and losses of a certain plan are generally defined in terms of the quantity of other goods and services which are equivalent in value to the various pros and cons of the plans being examined. For example, costs may be measured as opportunity costs or as the value of goods and services which provide a compensation necessary to restore the original level of well-being affected by the plan in question.

There are several approaches to the calculation of *shadow prices*, but it should be noted that they represent a second best solution to the allocation problem and in any case, they are not unambiguously determined.

Another important category of market failures contributing to environmental degradation is given by *externalities* [2, 4, 28, 32]. In the neoclassical framework, the value of a commodity is related to its price, so that the utility of a commodity can be reflected by means of an unambiguous quantitative measure. Free commodities (such as air and water) are assumed to have no price. In order to deal with the problem of consequences that are not priced at all in a market, neoclassical economists use the concept of external economies and diseconomies (externalities) already developed by Marshall by the end of the last century. Pollution can then be considered as an

external diseconomy. The necessity of operationalizing the externalities concept in environmental management has led to the well-known compensation idea. The compensation is based on the assumption that any occurrence of environmental externalities leads to a disturbance of the Pareto optimum. By offering next an amount of money which is sufficient to neutralize the shift in the utility level of the victim, one may restore the original equilibrium position. The compensation model can be regarded as a crucial tool in neoclassical economics, because only in this way one may assign an amount of money to environmental decay. The compensation model incorporates however, various limitations:

- it is normally a two party-model which reflects only the relative power and the income positions of the parties involved. But generally, the agents affected by pollution caused by specific activities are large in number. Most of them are often even not sufficiently aware of the damage. In any case it is practically impossible to strike a deal between the agents responsible for the pollution and all people who are affected or will eventually be affected. Furthermore, when the victims are a large set of individuals, the relative power of the polluter may determine the outcome of the compensation mechanism;
- the compensation model is essentially a partial analysis (since indirect impacts are not considered) and therefore may lead to inferior solutions;
- the compensation model is dependent on the jurisdictional framework;
- the compensation model does not aim at achieving a better environmental quality, but only at incorporating the environmental impacts in the traditional price and market system.

A concept connected to that of compensation is the one of *"willingness to pay"*. In order to determine the value of environmental goods and services, economists try to identify how much people would be willing to pay for these goods in artificial markets. Alternatively, the respondents could be asked to express their willingness to accept compensation. The limitations inherent in this method have been well formulated by Costanza [11]: "the quality of results in this method depends on how well informed people are; and does not adequately incorporate long-term goals since it excludes future generations from bidding in the markets. Furthermore, the problem with these techniques is that respondents may answer "strategically". For example, if they think their response may increase the probability of implementing a project they desire,

they may state a value higher than their true value".

Since the market prices do not reflect exactly the relative scarcity of environmental resources, it is necessary from a political economic point of view, in order to avoid an overexploitation of these resources, to impose appropriate *regulatory measures* by public authorities. In fact, since the rational decisions of individual agents lead necessarily to an outcome that is inconsistent with the best interests of society, a "*social trap*" exists [12]. As pointed out by Baumol and Oates [4], these measures can take the form of *direct regulations* (e.g. maximum pollution emissions) or the form of *economic disincentives* (pricing systems based on social costs in the form of taxes and subsidies). The main advantages of economic disincentives are:

- if high pollution goods are made sufficiently costly, their production and demand will decrease and then the negative effects on the environment do not accumulate;
- the administrative costs are low;
- technical progress capable of reducing pollution may be induced.

Such an approach seems reasonable since the main assumption is only that producers are always trying to reduce costs. Yet such an assumption may not be valid in some market forms. Furthermore, even in this type of approach there is a need for social assessment of the effects of pollution and for social evaluation of ecological goods, which implies the estimation of the quality of the environment that we want to restore or to preserve [24].

Recently, Costanza and Perrings have proposed a method called "*flexible environmental insurance bonding system*" inducing a strong economic incentive to research the true costs of environmentally innovative activities and to develop innovative cost-effective pollution control technologies [11].

3. Further Limitations of Cost-Benefit Analysis

Cost-benefit analysis focusses on efficiency criteria; equity problems are generally ignored. But, any policy decision affects the welfare positions of individuals, regions or groups in different ways; consequently, the public support for a certain policy decision will very much depend on the *distributional effects* of such a decision. These distributional issues are normally ignored in cost-benefit analysis, since only the sum - across all groups concerned - of monetized effects is taken into consideration. The underlying idea is that as long as the aggregate effect is positive, the

disadvantaged groups can in principle be compensated; however in practice such a compensation does usually not take place. Some revisions of cost-benefit analysis try to include distributional values directly in the analysis by using different weights for different social groups, or by computing the impact of the project on different income groups after which the alternatives are evaluated with respect to both their efficiency and equity.

The main limit of the first approach is that the subjective component inherent in this type of evaluation methods may increase to an unacceptable level. The second approach can clearly be better handled with multidimensional evaluation techniques.

It is noteworthy here that many essential elements of human life cannot be translated into a common denominator, whether money or not. Consequently, not only monetary consequences but also unpriced impacts of policy decisions have to be taken into consideration. Another adaptation of traditional cost-benefit analysis is the *shadow project approach*. This is an attempt to overcome the problem of intangibles in project evaluation. The idea is that the costs of deterioration of a natural area or of a historical building can be assessed from the costs of creating an equivalent project elsewhere (a so-called "shadow project"). The shadow project need not necessarily be actually implemented; it has only significance as an indirect step to gauge the costs of intangible losses of the original project. It is clear that a basic problem of the shadow concept is the definition of an equivalent project. Certain projects are unique as the result of a long historical, cultural or ecological development, so that the *time dimension* plays a crucial and sometimes prohibitive role in the definition of a shadow project. In addition, the *spatial dimension* may not be neglected, because the value of a certain project is co-determined by its accessibility. If the shadow project has a different accessibility, the compensating costs must be corrected for travel time differences. Furthermore, one should be aware of the fact that a shadow project has only a concrete meaning if its site is also known. The creation of a shadow project at a different place however, affects in turn the land use at that place; thus here again, a second shadow project would have to be defined in order to calculate the intangible losses due to the shadow project. In this way, a whole chain of shadow projects might be defined, which probably would lead to an indeterminate solution [33].

Intangible and incommensurable effects are very hard to incorporate in cost-benefit analysis; although many efforts have been undertaken, it is in practice almost impossible to place anything more sophisticated than arbitrary

numerical values on such effects. Therefore, the conclusion is justified that any attempt to transform a priori heterogeneous and unpriced impacts into a single dimension run the risk to fail.

The investment evaluation criterion generally used in order to compare intertemporal costs and benefits is the net present value (NPV). In financial economics, a distinction is made between *absolute and relative investment criteria* [9, 26]. The net present value, since it is an homogeneous linear function of the cash-flows, is an indicator of the financial convenience of an investment in absolute terms. This implies that the projects that present the greatest dimensions are always preferred, even if their mean convenience is lower than the one of the other projects. This again implies that the underlying assumption is that resources are considered to be unlimited. Other investment criteria such as the benefit-cost ratio or the internal rate of return are homogeneous functions of degree zero of the cash-flows and therefore, the financial convenience of a project is independent from the dimensions of such a project. These brief considerations make clear that the assumptions underlying each investment criterion are different and as a consequence also the results they generate are different. Therefore, we can conclude that even if all the evaluations in cost-benefit analysis could be correctly transformed in monetary values, the problem at hand is still multidimensional in nature!

4. Social and Environmental Limits to Economic Growth

Traditionally, income per capita has been used as a major criterion to evaluate economic developments, welfare increases, growth perspectives and the social value of plans. This view has also been criticized by several authors. Scitovski [37] has shown that there is no empirical evidence that the level of well-being grows more or less proportionally to the increase of priced commodities. According to Scitovski, our western society has already passed a saturation level of welfare, so that the perceived welfare is even declining. The perceived loss in environmental quality has even aggravated this tendency. The view that the quantitative and monetary value of production does not run parallel to the perceived individual and social utility was shared by Hirsch [22], who has demonstrated that the production process of the advanced countries does not break down on the physical limits to growth, but rather on the *social limits*. This indicates once more that human or social well-being is not a unidimensional variable. Is our traditional analytical framework able to incorporate conflicting issues caused by social and environmental costs?

Conventional economic frameworks are essentially based on a closed economic system consisting of a set of production functions, cost functions, and final demand functions, in which resources, commodities and services can in principle be generated in any combination within the system concerned. Furthermore, perfect information availability to all actors is assumed. Given these assumptions, the existence of a static equilibrium and different extensions to the dynamic case have been demonstrated in the economic literature [21]. But, real world economic systems are open systems utilizing material and energy resources provided by nature. Therefore, a series of interrelated feed-backs in the economic system has to be taken into account. As a consequence, as Georgescu-Roegen has correctly pointed out, the real economy is a *dissipative system*, not a self-perpetuating one [19]. Since in such a conventional system the highest quality resources are first exhausted, there is a need of replacing them with others requiring different and flexible technologies. In such an economic framework, it is less meaningful to talk about *environmental limits* to economic growth, since the extinction of any one species or the exhaustion of any one resource will automatically lead to investment in research into substitutes. Regarding this topic Costanza and Perrings write [11]: "In reality, however, the absence of markets for many environmental goods and services has resulted in technological innovations which permit harvest levels that can cause extinction or which overload the assimilative capacities of ecosystems through excessive production of wastes without stimulating research into backstop technologies. Therefore, even though ecotechnology can provide substantial benefits to society, the public (free) goods nature of its outputs will result in both underinvestment in basic research and underutilization of the technologies developed".

Traditionally, Gross National Product has been considered the best performance indicator of national economy and welfare. But if resource depletion and degradation are factored into economic trends, what emerges is a radically different picture from that depicted by conventional methods. Daly and Cobb [13] have attempted to adjust GNP to account mainly for depletions of natural capital, pollution effects and income distribution effects by producing an "Index of Sustainable Economic Welfare" (ISEW). A second version (ISEW2) also includes adjustments for depletion of non-renewable resources and long-term environmental damage. By this adjusted measure, Americans are much less "wealthy" than they seem. "If we continue to ignore natural ecosystems we may drive the economy down while we think we are building it

up. By consuming our natural capital, we endanger our ability to sustain income [13]".

5. Planning for Sustainability and Multiple Criteria Evaluation

The concept of sustainability has already a long history [1, 10, 15]. The most widely accepted definition of *sustainable development* is the one given by the World Commission on Environment and Development [40] where sustainable development is defined as paths of human progress which meet the needs and aspirations of the present generation without compromising the ability of future generations to meet their needs.

Goodland and Leduc define sustainable development as [20]: "a pattern of social and structural economic transformations which optimizes the benefits available in the present without jeopardising the likely potential for similar benefits in the future". This definition implicitly assumes a need to maintain yields from renewable natural systems over long periods of time.

Other approaches to the concept of sustainable development focus on the physical or natural resource base of any economy. Pearce [1] claims that sustainable development implies maintenance over time of aggregate resource stocks, such that the potential to generate welfare is not allowed to fall below the current level. Clearly, this viewpoint raises important questions concerning the measurability of environmental quality.

According to Costanza [10, 11], "sustainability does not necessarily mean a stagnant economy, but we must be careful to distinguish between "growth" and "development". Economic growth which is an increase in quantity cannot be sustainable indefinitely on a finite planet. *Economic development* which is an improvement in the quality of life without necessarily causing an increase in quantity of resources consumed, may be sustainable. Sustainable growth is an impossibility. Sustainable development must become our primary long-term policy goal".

In any case, the conclusion can be drawn that sustainable development cannot be measured by means of a single indicator, but it is multidimensional in nature. And consequently, environmental management is characterized by economic, political, environmental and ethical judgements. Therefore, in planning for sustainability, it is very difficult to arrive at straightforward, unambiguous solutions. This implies that such a planning process will always be characterized by the search for acceptable compromise solutions which requires an adequate evaluation methodology. Multiple criteria evaluation techniques aim at providing such a set of tools. In fact, during the last two

decades, it has increasingly been understood that welfare is a multidimensional variable which includes, inter alia, average income, growth, environmental quality, distributional equity, supply of public facilities, accessibility, etc. This implies that a systematic evaluation of public plans or projects has to be based on the distinction and measurement of a broad set of criteria. These criteria can be different in nature: private economic (investment costs, rate of return, etc.), socio-economic (employment, income distribution, access to facilities, etc.), environmental (pollution, deterioration of natural areas, noise, etc.), energy (use of energy, technological innovation, risk, etc.), physical planning (congestion, population density, accessibility, etc.) and so forth [31, 32].

From an operational point of view, five issues can be regarded as central to the concept of sustainable development. These are intergenerational equity, long-term uncertainty, inter-regional (spatial) links and trade-offs, multiple use, and economic-ecological integration [6]. Multicriteria evaluation seems to be a very useful tool for a systematic treatment of at least the last three issues (inter-regional links and trade-offs, multiple use, and economic-ecological integration). A proper use of multicriteria analysis presupposes however, the existence of an adequate environmental-economic model.

Nowadays, it is increasingly taken for granted that environmental and resource problems generally have at least far reaching economic and ecological implications, often of an unpriced nature. This implies that such problems are characterized inter alia by social, psychological, physico-chemical and geological aspects. Models aiming at structuring these cross-boundary problems of an economic and environmental nature are therefore called "*economic-environmental*" or "*economic-ecological*" models [8]. Since the complexity of this type of problems is high, there is a need for appropriate models offering a comprehensible and operational representation of a real world environmental situation. The strong quantitative tradition in economics has enabled researches to include environmental elements fairly easily in conventional models. Nevertheless, in integrating economic and environmental models, also some methodological problems have to be faced, such as *differences in time scales* (compared to ecology, economics is mainly analyzing short-term and medium term effects), *differences in spatial scales* (the spatial scale of many ecological variables is sometimes very low, whereas the scale of many economic variables is rather high) and *differences in measurement levels of the variables* (there is a clear need for methods

taking into account information of a "mixed" type).

In designing models for environmental and resource policy-making the following three main types of policy objectives may be distinguished [8]:

- (1) nature conservation objectives, e.g. "minimum exploitation of natural systems", "optimum yield";
- (2) socio-economic objectives, e.g. "maximum production of goods and services at minimum (private and social) cost";
- (3) mixed objectives, e.g. "maximum sustainable use of resources and environmental services".

It is clear that in policy-relevant economic-environmental evaluation models, socio-economic and nature conservation objectives are to be considered simultaneously. Consequently, multicriteria methods are in principle, an appropriate modelling tool for combined economic-environmental evaluation issues. For example, in modern resource management, the notion of multiple use is rather common.

Multiple use is the simultaneous use of natural resources, for different social and economic objectives, e.g. a forest which is used for outdoor recreation as well as timber production at the same time. Three broad categories of use of natural resources can be identified: *consumptive use*, *non-consumptive direct use* and *non-consumptive indirect use*. The terms consumptive and non-consumptive use are employed in an ecological sense, i.e. they refer to the resource population. Consumptive use of a resource may of course lead to production in an economic sense, i.e. income may be derived from transforming the resource into a marketable product [8, 10]. This can be clarified by referring to the case of water resources management, the essential economic implication of the term use is that water is no longer suitable for subsequent desirable uses, and costs must be incurred before the water can be used again. If one type of use of a water supply creates quality deterioration partially or wholly precluding another potential use of the water, then the water has been used consumptively. An important aspect of this problem of water use compared to other economic resources is that water has a wide *quality dimension* and different qualities of water are required for different uses [18].

Generally, ecosystems are used in several ways at the same time by a number of different users. This complies with the definition of multiple use. Such situations lead almost always to conflicts of interest and damage to the environment. The consequences range from suboptimal use due to unregulated access, to degradation of resource systems due to limited

knowledge of the ecological processes involved. Thus, In the area of environmental and resource management and in policies aiming at an ecologically sustainable development, many conflicting issues and interests emerge. As a tool for conflict management, multicriteria analysis is then an important evaluation method, which has demonstrated its usefulness in many environmental management problems.

In the context of conflicting interests, it is also noteworthy that in environmental management there is often an interference from local, regional or national government agencies, while there is at the same time a high degree of diverging public interests and conflicts among groups in society. At an *intraregional level* many conflicting objectives may exist between different actors (consumers, firms, institutions, etc.), which can formally be represented as multiple objective problems and which have a clear impact on the spatial organization of a certain area (e.g. industrialization, housing construction, road infrastructure construction). At a *multiregional level* various spatial linkages exist which affect through spatial interaction and spillover effects a whole spatial system (e.g. diffusion of environmental pollution, spatial price discrimination) and which in a formal sense can be described by means of a multiple objective programming framework. At a *supraregional level* various hierarchical conflicts may emerge between regional government institutions and the central government or between regional branches and the central office of a firm, which implies again a multiple objective decision situation.

From an operational point of view, the major strength of multicriteria methods is their ability to address problems marked by various conflicting interests. Multicriteria methods can provide systematic information on the nature of these conflicts so as to make the trade-offs in a complex situation more transparent to decision makers.

6. Multicriteria Evaluation: a Concise Overview

Since multicriteria methods are multidimensional in nature, most of the limitations inherent in cost-benefit analysis can be overcome. During the 70's and at the beginning of the 80's a great number of multicriteria methods were developed and used for different policy purposes in different contexts. The following distinctions can be made regarding the context and the scope of multicriteria evaluation methods:

- 1) discrete versus continuous methods;
- 2) multi-person versus single-person evaluations;
- 3) single-step versus multi-step evaluation procedures;

- 4) qualitative versus quantitative information.

Here, only the first and the fourth items will briefly be illustrated.

6.1. Continuous multiobjective methods

The main characteristic of multiobjective programming methods is that the feasible alternatives are only implicitly defined, so that in principle, their number is infinite. This problem has been analyzed by various authors who have developed a large number of theorems and algorithms [38].

An important concept is that of a *Pareto solution* (or non-dominated solution). A Pareto solution is based on the characteristic that the value of an objective function cannot be improved without reducing the values of the other objective functions.

A multiobjective programming method can be divided into two phases:

- generation of the set of efficient solutions,
- exploration of this set in order to find a "compromise solution".

Formally, let us consider a linear multiobjective problem:

max q
 subject to $q \in Q = \{f(x) : x \in X\}$
 where $f(x) = \{f_1(x), f_2(x), \dots, f_k(x)\} = Cx$
 and $X = \{x : Ax \leq b, x \geq 0\}$

where Cx expresses linear relationships between policy variables and policy objectives, and $Ax \leq b$ expresses linear constraints.

The following formal definition can be considered:

a point $x_0 \in X$ is *efficient* iff there is no other $x \in X$ such that $f_i(x) \geq f_i(x_0) \forall i=1, 2, \dots, k$ and $f_i(x) \neq f_i(x_0)$ for at least one $i \in k$.

The set of efficient solution vectors is denoted by Q^E .

In a continuous framework, efficient alternatives can be generated in three different ways:

- In theory it has been shown by Geoffrion that all the efficient solutions can be generated by solving the following scalar maximum problem:

max $m^t q$
 subject to $q \in Q$

where $m \geq 0$ is often normalized according to $m^{\text{te}} = 1$.

For simplicity, many authors transform the multiobjective problem into a parametric linear programming problem obtained by considering just one objective function obtained as a weighted sum of the various objective functions. Implicitly however, one assumes that the decision maker's utility function is - or, more realistically, may be approximated by - a linear function. In this case, the extreme points are sufficient to characterise the efficient frontier. There are, however, two problems in operating solely with efficient extreme points:

- in problems of a realistic size, the number of efficient extreme points is very large;
 - the decision-maker is not necessarily satisfied with an extreme point as an approximation to the most preferred solution: he may prefer certain intermediate points which are also efficient.
- A second way of generating efficient alternatives consists in a systematic variation of side-conditions. Thus, by optimizing one objective function under constraints on the other objective functions, which have to be varied in a systematic way, efficient alternatives are obtained.
- A third way of generating efficient alternatives consists in a systematic variation of weights in an objective function defining the distance between an appropriately chosen reference point and a feasible solution.

The exploration of the set of efficient solutions is made by means of interactive procedures. They proceed in a sequential way by alternating

- calculation steps
- evaluation steps.

At each calculation step the analyst proposes to the decision maker a compromise solution followed by a choice step consisting in the evaluation of this solution.

6.2. Discrete methods

A discrete multicriteria problem may be described in the following way [3, 31, 36]: A is a set of feasible actions (or alternatives); m is the number of different points of view or evaluation criteria g_i $i=1, 2, \dots, m$ considered relevant in a decision problem, where $g_i : A \rightarrow \mathbb{R}$, $\forall i=1, 2, \dots, m$ is a real valued function representing the i -th criterion according to a non decreasing

preference, while the action a is evaluated to be better than action b ($a, b \in A$) according to the i -th point of view iff $g_i(a) > g_i(b)$.

In this way a decision problem may be represented in a tabular or matrix form. Given the sets A (of alternatives) and G (of evaluation criteria) and assuming the existence of n alternatives and m criteria, it is possible to build an $n \times m$ matrix P called evaluation or impact matrix whose typical element p_{ij} ($i=1, 2, \dots, m; j=1, 2, \dots, n$) represents the evaluation of the j -th alternative by means of the i -th criterion. The impact matrix may include qualitative, quantitative or both types of information.

This general description implies that evaluation problems may lead to different kinds of outcomes; for instance, some methods only aim at determining a set of acceptable alternative solutions, while other methods aim at the selection of one ultimate alternative. Thus there is a range of multicriteria problem formulations, which may take one of the following forms [3,36]:

- (α) the aim is to identify one and only one final alternative;
- (β) the aim is the assignment of each action to an appropriate predefined category according to what one wants it to become afterwards (for instance, acceptance, rejection or delay for additional information);
- (γ) the aim is to rank all feasible actions according to a total or partial preorder;
- (δ) the aim is to describe relevant alternatives and their consequences.

7. Qualitative Versus Quantitative Information

It has been argued that the presence of qualitative information in evaluation problems concerning socio-economic and physical planning is a rule, rather than an exception [31]. Thus there is a clear need for methods taking into account qualitative information. In multicriteria evaluation theory, a clear distinction is made between quantitative and qualitative methods. Essentially, there are two approaches for dealing with qualitative information: a direct and an indirect one. In the *direct approach*, qualitative information is used directly in a qualitative evaluation method; in the *indirect approach*, qualitative information is first transformed into cardinal one, while next one of the existing quantitative methods is used. Cardinalization is especially attractive in the case of available information of a "mixed type" (both qualitative and quantitative data). In this case, the application of a direct method would usually imply that only the qualitative contents of all available (quantitative and qualitative) information is used, which would give rise to an

inefficient use of this. In the indirect approach, this loss of information is avoided; the question is of course, whether there is a sufficient basis for the application of a certain cardinalization scheme. An example of a multicriteria method that may use mixed information is the EVAMIX procedure; another interesting method for dealing with mixed information is the so-called REGIME method; this method is based on pairwise comparison operations [31].

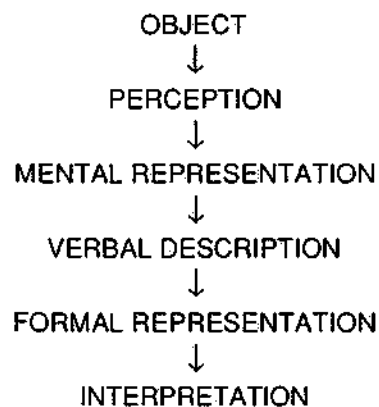
Another problem related to the available information concerns the uncertainty contained in this information. Ideally, the information should be precise, certain, exhaustive and unequivocal. But in reality, it is often necessary to use information which does not have those characteristics so that one has to face the uncertainty of a stochastic and/or fuzzy nature present in the data. In fact, if the available information is insufficient or delayed, it is impossible to establish exactly the future state of the problem faced, so that then a **stochastic uncertainty** is created. Another type of uncertainty derives from the ambiguity of this information, since in the majority of the particularly complex problems involving men, much of the information is expressed in linguistic terms, so that it is essential to come to grips with the fuzziness that is either intrinsic or informational typical of all natural languages. Therefore, a combination of the different levels of measurement with the different types of uncertainty has to be taken into consideration. The following taxonomy can be useful (see Figure 1).

	QUANTITATIVE INFORMATION	QUALITATIVE INFORMATION
CERTAINTY		
UNCERTAINTY		

Figure 1. Possible combinations of information measurement levels and uncertainty.

Stochastic uncertainty has been thoroughly studied in probability theory and statistics. **Fuzzy uncertainty** does not concern the occurrence of an event but the event itself, in the sense that it cannot be described

unambiguously. This situation is very common in human systems. Spatial-environmental systems in particular, are complex systems characterized by subjectivity, incompleteness and imprecision. Zadeh [41] writes: "as the complexity of a system increases, our ability to make a precise and yet significant statement about its behaviour diminishes until a threshold is reached beyond which precision and significance (or relevance) become almost mutually exclusive characteristics" (*incompatibility principle*). Therefore, in these situations statements as "the quality of the environment is good", "the unemployment rate is low" are quite common. Fuzzy set theory is a mathematical theory for modelling situations, in which traditional modelling languages which are dichotomous in character and unambiguous in their description cannot be used. Human judgments, especially in linguistic form, appear to be plausible and natural representations of cognitive observations. Psychological researchers represent this cognitive process in the following chain of transformations [16]:



Very little is actually known about the first two transformations, and therefore it is more appropriate to concentrate our attention on the third one (verbal description). Freksa [16] writes: "The distortion of information introduced in the third transformation appears to depend on the type of verbalization that is used. Numerical verbalizations seem to leave rather precise observations, but they appear imprecise in many observers, while linguistic verbalizations seem to preserve more information from these observers. We can explain this phenomenon by **cognitive distance**. A linguistic representation of an observation may require a less complicated transformation than a numerical representation, and therefore less distortion may be introduced in the former than in the latter. We could say that the linguistic representation is cognitively closer to the mental description than the numerical representation".

In traditional mathematics, variables are assumed to be precise, but when we are dealing with our daily language, imprecision usually prevails. Intrinsically, daily languages cannot be precisely characterized on either the syntactic or semantic level. Therefore, a word in our daily language can technically be regarded as a fuzzy set.

Fuzzy sets as formulated by Zadeh are based on the simple idea of introducing a degree of membership of an element with respect to some sets. Let us assume that the symbol U means the entire set (Universe of discourse). In classical set theory, given a subset A of U , each element $x \in U$ satisfies the condition: either x belongs to A , or x does not belong to A . The subset A is represented by a function $f_A: U \rightarrow [0, 1]$:

$$f_A(x) = \begin{cases} 1 & \text{if } x \in A \\ 0 & \text{if } x \notin A \end{cases}$$

The function f_A is called a characteristic function of the set A . Fuzzy sets are then introduced by generalizing the characteristic function f_A . Let U again be a universe of discourse. Let $x \in U$. Then a fuzzy set A in U is a set of ordered pairs

$$\{[x, \mu_A(x)]\}, \quad \forall x \in U$$

where $\mu_A: U \rightarrow M$ is a membership function which maps $x \in U$ into $\mu_A(x)$ in a totally ordered set M (called the membership set) and $\mu_A(x)$ indicates the grade of membership of x in A . Generally, the membership set is restricted to the closed interval $[0, 1]$. A fuzzy set is completely determined by its membership function. For $0 < \mu_A(x) < 1$, x belongs to A only to a certain degree; thus there is ambiguity in determining whether or not x belongs to A . The physical meaning is that a gradual instead of an abrupt transition from membership to non-membership is taken into account. A classical example is that of age. Let U be the set of all non-negative integers. Let us take into consideration the primary terms young and old. These terms can be considered the label of two fuzzy sets A and B . No doubt the ages 6 or 10 are young, whereas the ages 30 or 40 are less young. Thus it is possible to define a membership function $\mu_{A_{\text{young}}}$ showing the degree of compatibility of the age x to the concept of young.

It is indispensable however to clarify here a point of fundamental

importance: *the use of membership functions*. Membership functions constitute the essential basis on which the whole fuzzy set theory is built; they represent no doubt a brilliant idea which revolutionized traditional set theory, giving birth to a new mathematical field. But paradoxically, the membership functions constitute at the same time the strongest and the weakest point of the theory. Various scientists are sometimes sceptical about fuzzy sets for the main reason that they consider these membership functions too subjective. Therefore, it is necessary to address the question, on what factors such a subjectivity depends. Two essential factors may be distinguished here:

- 1) the **context** in which they are to be applied;
- 2) the **method** adopted in the building phase.

We will discuss these factors below in more detail.

The membership functions depend on the semantic contents of the subjective category they represent and therefore they vary according to the context in which they are to be applied. Then the question is whether this feature is really a negative one. In general, when an attempt is made to model a real world situation, the presence of a certain subjective component appears to be an inevitable phenomenon. Models by definition only give a partial representation of reality. As a consequence there are usually many alternative model formulations possible. There are several criteria available to judge whether a model is an adequate representation of reality. The way these criteria are applied contains inevitably a subjective element, as a one-to-one mapping between model and reality is an illusion.

The second step concerns the **building phase**. One way to build membership functions is to use deductive methods with the use of formal models constructed according to specific hypotheses. A second approach is empirical in nature. Here we can distinguish two cases:

- I) interpolating a finite number of degrees of membership,
- II) constructing a real model of a membership function and seeking to verify its empirical validity.

In our opinion, the empirical approach is more suitable for evaluation and decision models. Our position with respect to fuzzy set approaches in this context is that we regard the use of fuzzy sets desirable - or even necessary in some cases - for three reasons:

- I) it is possible to deal in a suitable manner with the ambiguity often present in available information;

- II) it is possible to do more justice to the subjective or creative component of the individual decision maker;
- III) it is possible to interact with a DSS (decision support system) in natural language by employing linguistic variables.

In the next section the empirical performance of ordinal and fuzzy multicriteria methods will be illustrated by means of a transportation problem.

8. Sensitivity Analysis of Qualitative Multicriteria Methods

Suppose that there are 3 possibilities for improving the transportation system in a region, viz. highway construction, a road/bus system and a new train (railroad) system. Each of these 3 alternatives will be judged on the basis of 5 criteria, viz. costs, travel time, capacity, NO_x emissions and landscape impacts. Some of these impacts are quantitative, but others are qualitative in nature. The qualitative part of the relevant information for this problem can be formulated both in ordinal and fuzzy terms. We will first apply a multicriteria method able to treat ordinal information viz. the REGIME method, and then a fuzzy multicriteria procedure will be used.

The ordinal impact matrix related to the above problem is supposed to be the following:

Criteria	Units	Highway	Road/bus	Train	Weights
Costs	mln gld	200	250	400	++
Travel Time	---/+++	+++	++	+	+
Capacity	mln km/year	20	30	40	+++
NO _x Emissions	ton/year	1000	750	100	+++
Landscape	---/+++	---	---	-	+

The ---/+++ scale is interpreted as an ordinal scale.

Table 1. Ordinal evaluation matrix of a transportation problem

Given this information of a mixed (cardinal/ordinal) type, there is a need to apply a multicriteria method suitable for such information. An interesting method for dealing with mixed information is the so-called REGIME method [31]. To some extent regime analysis can be interpreted as an ordinal generalization of pairwise comparison methods such as concordance

analysis [36]. Its point of departure is an ordinal evaluation matrix and an ordinal weight vector. Given the ordinal nature of the evaluation criteria, by means of pairwise comparison of alternatives, no attention is paid to the size of the difference between the impacts of alternatives; it is only the sign of the difference that is taken into account. Ordinal weights are interpreted as originating from unknown quantitative weights. A set S is defined containing the whole set of quantitative weights that conform to the qualitative priority information. In some cases the sign will be the same for the whole set S , and the alternatives can be ranked accordingly. In other cases the sign of the pairwise comparison cannot be determined unambiguously. This difficulty is circumvented by partitioning the set of feasible weights so that for each subset of weights a definite conclusion can be drawn about the sign of the pairwise comparison. The distribution of the weights within S is assumed to be uniform and therefore the relative sizes of the subsets of S can be interpreted as the probability that alternative a is preferred to alternative b . Probabilities are then aggregated to produce an overall rating of the alternatives, based on a success index or success score.

By applying the regime method to the problem described above the following matrix of relative pairwise success indices is obtained:

	Highway	Road/bus	Train
Highway	-	0.30	0.00
Road/bus	0.70	-	0.01
Train	1.00	0.99	-

From this table it is clear that the train option is the most preferable alternative, followed by road/bus and highway. The value 1.00 in the comparison between train and highway alternatives indicates that for this comparison no added value is to be expected from a measurement of these criteria on a higher measurement scale. The probability that, given the ordinal information on travel time and landscape, the road/bus alternative ranks higher than the highway alternative equals 70%.

Now the same transportation problem will be formulated within fuzzy terms. Recently a new discrete multicriteria model whose impact (or evaluation) matrix may include either crisp, stochastic or fuzzy measurements of the performance of an alternative a_n with respect to a criterion g_m has been developed by the present authors [30]. This method will briefly be described

here. It can be subdivided into four main steps.

1) Definition of a Fuzzy Region of Satisfactory Alternatives

Given a "consistent family" of mixed evaluation criteria $G=\{g_m\}$, $m=1,2,\dots,M$, and a finite set $A=\{a_n\}$, $n=1, 2,\dots, N$ of potential alternatives (actions), a region of satisfactory alternatives can be obtained by defining a fuzzy interval of feasible and acceptable values for each criterion.

From an operational point of view, in public decision making a single point-value solution (e.g. weights) tends to lead to deadlocks in the evolution of the decision process because it imposes too rigid conditions for a compromise. On the contrary, when a higher degree of flexibility is allowed, the definition of a fuzzy region of satisfactory solutions could in principle make more room for mutual consensus.

2) Comparison of Fuzzy Sets

In order to overcome some of the limitations typical of fuzzy approaches to multicriteria evaluation, we have developed a new distance metric (preference index) that is useful in the case of continuous membership functions allowing also a definite integration. The main characteristic of this semantic distance is the comparison of fuzzy sets by means of areas instead of intersections or α -cuts.

3) Pairwise Comparison of the Alternatives

Evaluation requires normally a judgement of the relative performance of distinct alternatives based on dominance relationships.

Six different fuzzy relations are considered:

- 1) much greater than (\gg)
- 2) greater than ($>$)
- 3) approximately equal to (\cong)
- 4) very equal to ($=$)
- 5) less than ($<$)
- 6) much less than (\ll)

Given such information on the pairwise performance of the alternatives according to each single criterion, it is necessary to aggregate these evaluations in order to take into account all criteria simultaneously; this is done taking into account the degree of compensation to be introduced in the model, and a measure of the "incertitude" of the evaluations given by the

entropy concept.

4) Evaluation of the Alternatives

The information provided by such "fuzzy preference relation" can be used in different ways, e.g., the degree of truth (τ) of statements as

"according to most of the criteria

- **a** is better than **b**,
- **a** and **b** are indifferent,
- **a** is worse than **b**"

can be computed by means of proportional linguistic quantifiers and approximate reasoning rules.

Such pairwise evaluations can be used directly by the decision-maker(s) in order to isolate a set of satisfactory solutions, or if in a given decisional environment there is a need to perform further elaborations in order to get a ranking of the alternatives (in a complete or partial preorder), this can also be done by using further elaborations of approximate reasoning taking into account the entropy levels and the relations with all other actions.

The fuzzy impact (or evaluation) matrix related to the above transportation problem is supposed to be the following:

Criteria	Units	Highway (a ₁)	Road/bus (a ₂)	Train (a ₃)
Costs	mln gld	200 (.1)	250 (.1)	400 (.6)
Travel Time	linguistic	excellent (.1)	good (.85)	moderate (.6)
Capacity	mln km/year	20 (.5)	30 (.8)	40 (.1)
NO _x Emissions	ton/year	1000 (.3)	750 (.6)	100 (.1)
Landscape	linguistic	bad (.2)	bad (.2)	moderate (.6)

(the values in brackets are the membership degrees of each action to the interval of feasible and acceptable values defined on each criterion)

Table 2. Fuzzy evaluation matrix of a transportation problem

By applying our fuzzy multicriteria procedure for each pair of actions, the following degrees of truth τ of a linguistic evaluation are obtained:

a_1 is better than a_2	$\tau=0$
a_1 and a_2 are indifferent	$\tau=0$
a_1 is worse than a_2	$\tau=0.57$
a_1 is better than a_3	$\tau=0.67$
a_1 and a_3 are indifferent	$\tau=0$
a_1 is worse than a_3	$\tau=1$
a_2 is better than a_3	$\tau=0.53$
a_2 and a_3 are indifferent	$\tau=0$
a_2 is worse than a_3	$\tau=1$

Then based on the procedure described in [30] we obtain the following preorder:

$$a_3 \rightarrow a_2 \rightarrow a_1$$

This ranking is a function of all actions taken into consideration; on the contrary, the pairwise linguistic evaluations give information only on each single pair of actions. Thus both together can help the decision-maker(s) to reach a final decision.

It is noteworthy that the overall ranking derived from both methods is the same; thus a corroboration of the results is obtained. However, by using the REGIME method the differences between pairs of actions are less extreme because REGIME does not take into account degrees of difference (intensity of preference) between actions.

9. Concluding Remarks

In the above application we have shown that multicriteria methods provide a flexible way of dealing with qualitative environmental effects of decisions. However, this does not mean that multicriteria evaluation is a panacea which can be used in all circumstances without difficulties. It has its own problems, and some of these problems will be briefly addressed in this concluding section.

- 1) Since different conflicting evaluation criteria are taken into consideration, a multicriteria problem is mathematically ill-defined. Thus a complete axiomatization of multicriteria decision theory is very difficult.
- 2) Neither an absolutely consistent decision maker nor a complete objectivity and value neutrality are assumed in multicriteria analysis; the

principal aim of multicriteria decision aid (MCDA) is supposed to be not to discover a final unambiguous solution, but "to construct or create something which is viewed as liable to help an actor taking part in a decision process either to shape, and/or to argue, and/or to transform his preferences [35]". But one has to recognize that the main approaches by which value statements are taken into account in MCDA models (weighting of criteria and interactive procedures) have to be dealt with carefully.

3) Finally, it should be noticed that the results of any decision model depend on the available information; this information may assume different forms. But, it has to be noted that this available information depends on the problem definition phase, which briefly may be described as the process through which data are transformed into information. The information used as input for decision models may be handled and structured in different ways; this means that when an attempt is made to model a real world situation, the presence of a certain subjective component appears to be an inevitable phenomenon. Thus the use of evaluation models depends in this framework *on the ability of the researcher constructing the model*. It is important to keep this in mind when MCDA methods are used to "justify" or "defend" political decisions.

REFERENCES

- 1) Archibugi F., Nijkamp P. (eds.)-Economy and Ecology: towards sustainable development, Kluwer, Dordrecht, 1990.
- 2) Ayres R.U., Kneese A.V.-Externalities: economics and thermodynamics, in Archibugi F., Nijkamp P. (eds.)-Economy and Ecology: towards sustainable development, Kluwer, Dordrecht, 1990, pp.89-118.
- 3) Bana e Costa C.A. (ed.)- Readings in multiple criteria decision aid, Springer-Verlag, Berlin, 1990.
- 4) Baumol W.J. and Oates W.E.-The theory of environmental policy, Prentice-Hall, Englewood Cliffs, 1975.
- 5) Bell D.E., Keeney R.L. and Raiffa H. (eds.)- Conflicting objectives in decision- International series on applied systems analysis- J. Wiley and Sons, New York, 1977.
- 6) van den Bergh J.C.J.M., Nijkamp P.- Operationalizing sustainable development: dynamic ecological economic models, Ecological Economics, 4 (1991), pp.11-23.
- 7) Bojo J., Maler K.G. and Unemo L.- Environment and development: an economic approach, Kluwer Academic Publishers, Dordrecht, 1990.
- 8) Braat L.C., Van Lierop W.F.J. (eds.)- Economic-ecological modeling, North-Holland, Amsterdam, 1987.
- 9) Brealey R., Myers S., Principles of corporate finance, McGraw Hill, New York, 1985.
- 10) Costanza R. (ed.)- Ecological Economics: the science and management of sustainability, Columbia University Press, New York, 1991.
- 11) Costanza R., Perrings C.-A flexible assurance bonding system for improved environmental management, Ecological Economics 2 (1990), pp. 57-75.
- 12) Costanza R.-Social traps and environmental policy, BioScience, 37, 1987, pp.407-412.
- 13) Daly H., Cobb J.J.-For the common good: redirecting the economy toward community, the environment and a sustainable future, Beacon Press, Boston, 1990.
- 14) Dasgupta A.K., Pearce D.W.- Cost-benefit analysis, MacMillan, London, 1972.
- 15) Folke C., Kaberger T.-Linking the natural environment and the economy: Essays from the Eco-Eco Group, Kluwer, Dordrecht, 1991.
- 16) Freksa C.- Linguistic description of human judgements in expert systems

and in the "soft sciences", in Gupta M.M. and Sanchez E. (eds.)- Approximate reasoning in decision analysis, North-Holland, Amsterdam, 1982, pp. 297-305.

17) Funtowicz S.O., Ravetz J. R.- A new scientific methodology for global environmental issues, in R. Costanza (ed.)- Ecological Economics, New York, Columbia, pp. 137-152, 1991.

18) Funtowicz S.O., Munda G., Paruccini M.- The aggregation of environmental data using multicriteria methods, to appear in Environmetrics, 1993.

19) Georgescu-Roegen N.-The entropy law and the economic process, Harward University Press, Cambridge MA, 1971.

20) Goodland R., Leduc G.-Neoclassical economics and principles of sustainable development, Ecological Modeling, vol.38, pp.19-46, 1987.

21) Hildenbrand W., Kirman A.P.- Equilibrium analysis, North-Holland, Amsterdam, 1991.

22) Hirsch F.-Social limits to Growth, Harward University Press, Cambridge Mass., 1976.

23) Korhonen P., Wallenius J.- A careful look at efficiency and utility in multiple criteria decision making: a tutorial, W.P., Helsinki School of Economics, F-197, 1988.

24) Lombardini S.-Prolegomena to a theory of economic development, Rivista Internazionale di Scienze Economiche e Commerciali, XXXIV, N.10, 1987.

25) Maler K.G.-Environmental economics, The Johns Hopkins Press, Baltimore, 1974.

26) Matarazzo B.- Sulla scelta degli investimenti privati, Univ. Catania, Ist. of Mathematics, 1981.

27) Mishan E.J.-Cost-benefit analysis, Allen and Unwin, London, 1971.

28) Mishan E.J.-The postwar literature on externalities: an interpretative essay, Jour. of Economic Literature, 9 (1), 1971, pp.1-28.

29) Munda G., Nijkamp P. and Rietveld P.- Information precision and evaluation methods, to appear in Giardina E., Williams A. (eds.)- Efficiency in the public sector, Edward Elgar, 1993.

30) Munda G., Nijkamp P. and Rietveld P.- Qualitative multicriteria methods for fuzzy evaluation problems, 1992.

31) Nijkamp, P., Rietveld P. and Voogd H.- Multicriteria evaluation in physical planning, North-Holland, Amsterdam, 1990.

32) Nijkamp P. -Environmental policy analysis- New York, Wiley, 1980.

33) Nijkamp P., van Delft A.- Multicriteria analysis and regional decision-

making, Martinus Nijhoff, Leiden, 1977.

34) Pearce D.W., Nash C.A.- The social appraisal of projects, MacMillan, London, 1989.

35) Roy B.- Decision aid and decision making, in Bana e Costa C.A. (ed.)- Readings in multiple criteria decision aid, Springer-Verlag, Berlin, pp. 17-35, 1990.

36) Roy B.-Méthodologie multicritere d' aide à la decision, Economica, Paris, 1985.

37) Scitovski T.-The joyless economy, Oxford University Press, New York, 1976.

38) Steuer R.E.- Multiple criteria optimization- Wiley, New York, 1986.

39) Tinbergen J.- Economic policy: principles and design, North-Holland, Amsterdam, 1956.

40) World Commission on Environment and Development-Our common future, Oxford University Press, Oxford, 1987.

41) Zadeh L.A.- Fuzzy sets, Information and Control, 8, 1965, pp. 338-353.

42) Zimmermann H.J.-Fuzzy set theory and its applications, Kluwer-Nijhoff Publishing, Boston, 1986.

43) Zimmermann H.J.-Fuzzy sets, decision making, and expert systems, Kluwer-Nijhoff Publishing, Boston, 1987.

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